# LIGHT SPREAD IN PHOTOGRAPHIC EMULSION – AN EXPERIMENTAL INVESTIGATION

BY

L. O. HENDEBERG

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**INAUGURAL DISSERTATION**

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**L. O. HENDEBERG**

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By L. O. Hendeberg

The thesis includes this summary and the following two papers which will be referred to by Roman numerals:

I. Contrast transfer function of the light diffusion in photographic emulsions. Arkiv Fysik *16*, 417 (1960).

II. Photographic transfer functions experimentally related to the illuminating apertures. Arkiv Fysik (in printing).

Light scattering in photographic emulsion is studied by combining the transfer functions of the separate links in an imaging chain. The purpose of paper I is therefore to investigate conditions necessary for building up the line image in order to distinguish the component influences in a complex combination of optical devices. These investigations show that it is possible to control the influences of diffractions and aberrations obtained from an illuminating objective and non-linearity obtained at the development procedure. But nobody seems to have used the favourable application described in I for extended studies of the influences of different illuminating apertures on light spread in emulsion. This "cone-effect" is investigated in paper II as a continuation of the first mentioned paper.

Examinations of the behaviour of the emulsion, when it is illuminated by a convergent bundle of light, for example, are usually made by some resolving power test. However, the resolution limit is closely related to a strong decrease in the function $|T(N)|$ obtained by a spatial Fourier transform of the light spread function ($N$ is spatial frequency in lines/mm). It is therefore advisable to make several determinations of the transform, i.e. the decrease in modulation of a spatial frequency component through the system. The common purpose of the two papers, I and II, forming this thesis was to determine the photographic transfer function $|T_{em}(N)|$. The inverse Fourier transform gives the spread function $\varphi_{em}(x)$, of the light scattering in the emulsion (I), where $x$ is defined as a length coordinate.

The basic assumption in I and II was that the Fourier transform

$|T_{tot}(N)|$ of the photographic image is a product of the individual Fourier transforms of the intensity function of the object as well as of the spread functions of the optical system, the photographic emulsion, and the scanning system. In this chain of transforms only the light spread function of the photographic emulsion cannot directly be experimentally determined and is therefore calculated from the above-mentioned product.

The one-dimensional Fourier transforms (the transfer functions) are measured by exposing one-dimensional objects consisting of periodic line patterns with sinusoidal intensity distribution perpendicular to the lines and with constant intensity parallel to their extension. The pattern is described by its frequency and its modulation which is the ratio between the amplitude of the lines and their mean intensity. The quotient between the modulation of the image pattern and that of the object gives the modulus of the transfer function of the imaging system for the particular frequency used.

By using the arrangement developed in I and II, the linearity in transferred intensity was experimentally examined to hold for some combinations of optics, emulsions, and developers. The patterns of the object maintain the sinusoidal shape straight through the imaging chain, for only the fundamental frequency appears when the pattern is described in the exposure units (I). A change in the modulation of the object gives a proportional change in the image. Furthermore, as shown in I, the function $|T_{em}(N)|$ is constant over the limited imaging field when the principal ray passes obliquely through the illuminating objective. Such a problem does not exist in the exposure arrangement described in II. However, during development some adjacency effects always seem to appear. But these nonlinearities do not disturb the experiments as the small magnitudes of the fringe effect show.

The light spread caused by the optical system of the apparatus used for exposing the patterns onto the emulsion, was separately examined. The amount of spread was measured in such a way that the optical system images a 2.6 $\mu$m pinhole, the image of which was Fourier-analyzed giving $|T_{opt}(N)|$. However, as it is necessary to illuminate the pinhole from behind by a condenser system, the image is obtained

by unintentionally partially coherent light. But the agreement with the preferably incoherent imaging — necessary for treating image transfer properties in Fourier language — is satisfactory if the source is incoherent and the numerical aperture of the condenser is more than twice that of the collecting objective in the optical system.

The transfer function, $|T_{\text{phot}}(N)|$, of the microphotometer used in the recording of the variation in transmission of the photographic images was determined by an edge test, i.e. by scanning an image of an edge, as described in II.

The determinations performed in this work were limited to commercial emulsions, whose thickness and ingredients must be accepted. The developers, Final for the Agfa films in I and Microphen for the Ilford films in II, are commonly considered to give images with low adjacency effects which was also confirmed by the results in these papers. Furthermore, the development technique had to be carefully elaborated. Two different procedures, brush development and ultrasonic agitation development, gave equivalent and acceptable results without disturbing adjacency effects (II). In paper II it is also shown that moderate variations of the development time (from 3 to 16 minutes) to different slopes, $\gamma$, of the characteristic density curve have no influence on the function $|T_{\text{em}}(N)|$. In density units the resolving power changes considerably, but various mean intensities of the sinusoidal patterns have no noticeable influence on the result, provided that the intensities are within generally used exposure ranges, and exposure units are used. These facts facilitate, of course, the measurements and interpretations considerably. At the same time it is a way to assure linear treatment of the system.

In order to obtain high-quality measurements the characteristic density must be determined with extreme precision (II). It is therefore necessary to use the same apparatus for exposing both the density wedges and the sinusoidal line patterns. However, there exists a moderate variation in exposure time depending on the particular exposure method, for the emulsion passes a fixed slit image, the width of which depends on the aperture. The characteristic density curves are nevertheless equivalent in spite of variations in exposure time and different illuminating apertures (II). On the basis of this it is

advisable to combine a few curves to a common characteristic density curve in order to eliminate errors in the measurements statistically.

Among other results the following ought to be pointed out. The spread of light is in general less for fine-grained films than for coarse-grained ones (I). However, not only mean grain size will influence the measurements but also the thickness of the emulsion in a batch and the spectral distribution of the illuminating light. Many exceptions from these generalizations exist. The papers I and II show that two different batches of the same type of emulsion often give quite different transfer functions. In paper I the emulsion Agfa IF is shown to give half-value widths of the line-spread function varying from 4.8 to 3.2 $\mu$m and a corresponding variation in the tenth-value width from 12 to 10 $\mu$m. The same variations may also be found in different batches of Agfa IU and Ilford Pan F.

The light spread in the photographic emulsion is represented by either a line-spread function, $\varphi_{em}(x)$, or by its Fourier transform $|T_{em}(N)|$, of which the last-mentioned is convenient to determine experimentally and has therefore been investigated. One of the type $(1 + N^2)^{-1}$ is fitted to the experimental transfer function of an Agfa IF emulsion as shown in I. This type of one-parameter assumption fits the experimental curves quite well, as also pointed out by Frieser [1], Paris [2], and Som and Ghosh [3]. Sayanagi [4] proposed an assumption of the type $(1 + N^2)^{3/2}$ which also agrees quite well with the curves. Paris has also shown this by using the Gaussian method of least squares. However, other functions, e.g. the Gaussian type $\exp(-N^2)$, and the type $\exp(-N)$, do not correlate well with the experimental data.

For some years it has been common to characterize the light spread in the photographic emulsion by a technique similar to that applied in papers I and II. To go further and study the behaviour of $|T_{em}(N)|$ at various illuminating apertures is complicated by those marginal rays of the illuminating cone of light which enter the emulsion at an oblique angle. When the illuminating aperture increases, the light-bundle is spread out and the light spread function, $\varphi_{em}(x)$, may be extended. Nobody seems, however, to have used the method described in I to study the transfer function at various illuminating apertures

and to co-ordinate the results. Other arrangements have been used by many scientists in order to solve the problem. However, different results are frequently obtained. In some cases apertures smaller than *f*/1.5 have no influence on the results, whereas in other cases apertures smaller even than *f*/5.6 have a marked effect when the frequency is as low as $N = 30$ mm$^{-1}$.

In spite of diffractions and aberrations caused by an optical system it was possible (II) to separate function $|T_{em}(N)|$ from the image function $|T_{tot}(N)|$. An effective analysis of the combined effect of optics and emulsion has been facilitated by a high precision in the apparatus used for exposing the emulsion and for lens testing as well as by great care in the development procedure and in the scanning of the image.

The transfer functions $|T_{em}(N)|$ obtained from the product, $|T_{tot}(N)|$, by using known experimental data show (in II) a small tendency to decrease when the aperture increases. The function $|T_{em}(N)|$ is constant when $N \leqq 15$ mm$^{-1}$, but decreases by about 0.02 when the aperture increases from *f*/16 to *f*/1.5 for $N = 23$ mm$^{-1}$. At larger spatial frequencies $|T_{em}(N)|$ decreases by about 0.03. These tendencies are clearly discernible in all investigated types of the Ilford emulsions Micro Neg Pan, Pan F, and FP3. Only few exceptions were obtained for FP3 at some high frequencies.

A rough statistical analysis shows, however, that $|T_{em}(N)|$ also may be constant in the whole investigated aperture region. This inaccuracy depends primarily on the determination of $|T_{opt}(N)|$ which is strongly dependent on the precision in the stop settings made at the smallest and largest apertures.

The line image in the emulsion in the imaging plane depends considerably on the aperture of the illuminating cone of light and on its focusing relative to the film, as measurements of the transfer functions $|T_{tot}(N)|$ indicate. The technique of studying the product of the transfer functions makes it possible to separate the influences of the individual links in the imaging chain. The conditions which must be fulfilled for an optimization of the image function, $|T_{tot}(N)|$, at an illuminating aperture between *f*/2 and *f*/2.8 are consequences of an almost constant value of $|T_{em}(N)|$ of the emulsion, and a large variation of $|T_{opt}(N)|$.

This optimum setting depends in this case very little on the frequency, as $|T_{opt}(N)|$ has its maximum at nearly the same focus position for all frequencies used. As the function, $|T_{em}(N)|$, is also independent of the position of the film, the optimum conditions exist at the same aperture setting as above and at the best focus position irrespective of the spatial frequency. However, a defocus of 0.03 mm from the best focus position displaces the optimum to a much smaller aperture ($f/8$). The depth of field is great at small apertures of the lens.

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